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## Effects of Residue Background Events in Direct Detection Experiments on Identifying WIMP Dark Matter

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We reexamine the model-independent data analysis methods for extracting properties of Weakly Interacting Massive Particles (WIMPs) by using data (measured recoil energies) from direct Dark Matter detection experiments directly and, as a more realistic study, consider a small fraction of residue background events, which pass all discrimination criteria and then mix with other real WIMP-induced signals in the analyzed data sets. In this talk, the effects of residue backgrounds on the determination of the WIMP mass as well as the spin-independent WIMP coupling on nucleons will be discussed.

*Keywords:* Dark Matter; WIMP; direct detection; background.

### 1. Introduction

In our earlier work on the development of model-independent data analysis methods for extracting properties of Weakly Interacting Massive Particles (WIMPs) by using measured recoil energies from direct Dark Matter detection experiments directly<sup>1,2,3,4</sup>, it was assumed that the analyzed data sets are background-free, i.e., all events are WIMP signals. Active background discrimination techniques should make this condition possible. For example, by using the ratio of the ionization to recoil energy, the so-called “ionization yield”, combined with the “phonon pulse timing parameter”, the CDMS-II collaboration claimed that electron recoil events can be rejected event-by-event with a misidentification fraction of  $< 10^{-6}$ .<sup>5</sup> The CRESST collaboration demonstrated also that the pulse shape discrimination (PSD) technique can distinguish WIMP-induced nuclear recoils from those induced by backgrounds by means of inserting a scintillating foil, which causes some additional scintillation light for events induced by  $\alpha$ -decay of  $^{210}\text{Po}$  and thus shifts the

pulse shapes of these events faster than pulses induced by WIMP interactions in the crystal<sup>6, a</sup>.

However, as the most important issue in all underground experiments, possible residue background events which pass all discrimination criteria and then mix with other real WIMP-induced events in our data sets should also be considered. Therefore, as a more realistic study, we take into account small fractions of residue background events mixed in experimental data sets and want to study how well the model-independent methods could extract the *input* WIMP properties by using these “impure” data sets and how “dirty” these data sets could be to be still useful.

In this article, I focus on two properties of WIMP Dark Matter: the mass  $m_\chi$  and the spin-independent (SI) coupling on nucleons  $f_p$ . More detailed discussions can be found in Refs. 8, 9.

## 2. Effects of residue background events

In our numerical simulations based on the Monte Carlo method, while the shifted Maxwellian velocity distribution<sup>10,1</sup> with the standard values of the Sun’s orbital velocity and the Earth’s velocity in the Galactic frame:  $v_0 \simeq 220$  km/s and  $v_e = 1.05 v_0$ , and the Woods–Saxon form for the elastic nuclear form factor for the spin-independent WIMP–nucleus interaction<sup>11,10</sup> have been used for generating WIMP-induced signals, a *target-dependent exponential* form for residue background events has been introduced<sup>8</sup>:

$$\left(\frac{dR}{dQ}\right)_{\text{bg,ex}} = \exp\left(-\frac{Q/\text{keV}}{A^{0.6}}\right). \quad (1)$$

Here  $Q$  is the recoil energy,  $A$  is the atomic mass number of the target nucleus. The power index of  $A$ , 0.6, is an empirical constant, which has been chosen so that the exponential background spectrum is somehow *similar to*, but still *different from* the expected recoil spectrum of the target nucleus (see Figs. 1); otherwise, there is in practice no difference between the WIMP scattering and background spectra. Note that, the atomic mass number  $A$  has been used here just as the simplest, unique characteristic parameter in the analytic form (1) for defining the residue background spectrum for *different* target nuclei. It does *not* mean that the (superposition of the real) background spectra would depend simply/primarily on  $A$  or on the mass of the target nucleus,  $m_N$ .

Note also that, firstly, the exponential form (1) for residue background spectrum is rather naive; however, since we consider here *only a few (tens) residue* background events induced by perhaps *two or more* different sources, pass all discrimination criteria, and then mix with other WIMP-induced events in our data sets of  $\mathcal{O}(100)$  *total* events, exact forms of different background spectra are actually not very important and this exponential spectrum should practically not be unrealistic. Secondly, our model-independent data analysis procedures requires only measured recoil energies

<sup>a</sup>More details about background discrimination techniques and status see also e.g., Refs. 7.

from one or more experimental data sets with different target nuclei<sup>1,2,3,4</sup>. Hence, for applying these methods to future real direct detection data, the prior knowledge about (different) background source(s) is *not required at all*.

Moreover, the maximal cut-off of the velocity distribution function has been set as  $v_{\max} = 700$  km/s. The experimental threshold energy has been assumed to be negligible and the maximal cut-off energy is set as 100 keV. The background window (the possible energy range in which residue background events *can not be ignored*, compared to some other ranges) has been assumed to be the same as the experimental possible energy range. Note here that the actual numbers of generated signal and background events in each simulated experiment are Poisson-distributed around their expectation values *independently*, and the total event number in one experiment is then the sum of these two numbers; both generated signal and background events are treated as WIMP signals in our analyses. Additionally, we assumed that all experimental systematic uncertainties as well as the uncertainty on the measurement of the recoil energy could be ignored.

### 2.1. On the measured recoil spectrum

In Figs. 1 I show measured energy spectra (solid red histograms) for a  $^{76}\text{Ge}$  target with three different WIMP masses: 25 (top), 100 (middle), and 500 (bottom) GeV. While the dotted blue curves show the elastic WIMP-nucleus scattering spectra, the dashed green curves indicate the exponential background spectrum given in Eq. (1), which have been normalized so that the ratios of the areas under these background spectra to those under the (dotted blue) WIMP scattering spectra are equal to the background-signal ratio in the whole data sets. 5,000 experiments with 500 total events on average in each experiment have been simulated.

It can be found here that, the shape of the WIMP scattering spectrum depends highly on the WIMP mass: for light WIMPs ( $m_\chi \lesssim 50$  GeV), the recoil spectra drop sharply with increasing recoil energies, while for heavy WIMPs ( $m_\chi \gtrsim 100$  GeV), the spectra become flatter. In contrast, the exponential background spectra shown here depend only on the target mass and are rather *flatter/sharper* for *light/heavy* WIMP masses compared to the WIMP scattering spectra. This means that, once input WIMPs are *light/heavy*, background events would contribute relatively more to *high/low* energy ranges, and, consequently, the measured energy spectra would mimic scattering spectra induced by *heavier/lighter* WIMPs. Moreover, for heavy WIMP masses, since background events would contribute relatively more to *low* energy ranges, the estimated value of the measured recoil spectrum at the experimental threshold energy could thus be (strongly) overestimated.

### 2.2. On determining the WIMP mass

Fig. 2 show the *median* values of the reconstructed WIMP mass and the lower and upper bounds of the  $1\sigma$  statistical uncertainty by means of the model-independent procedure introduced in Refs. 2 with mixed data sets from WIMP-induced and

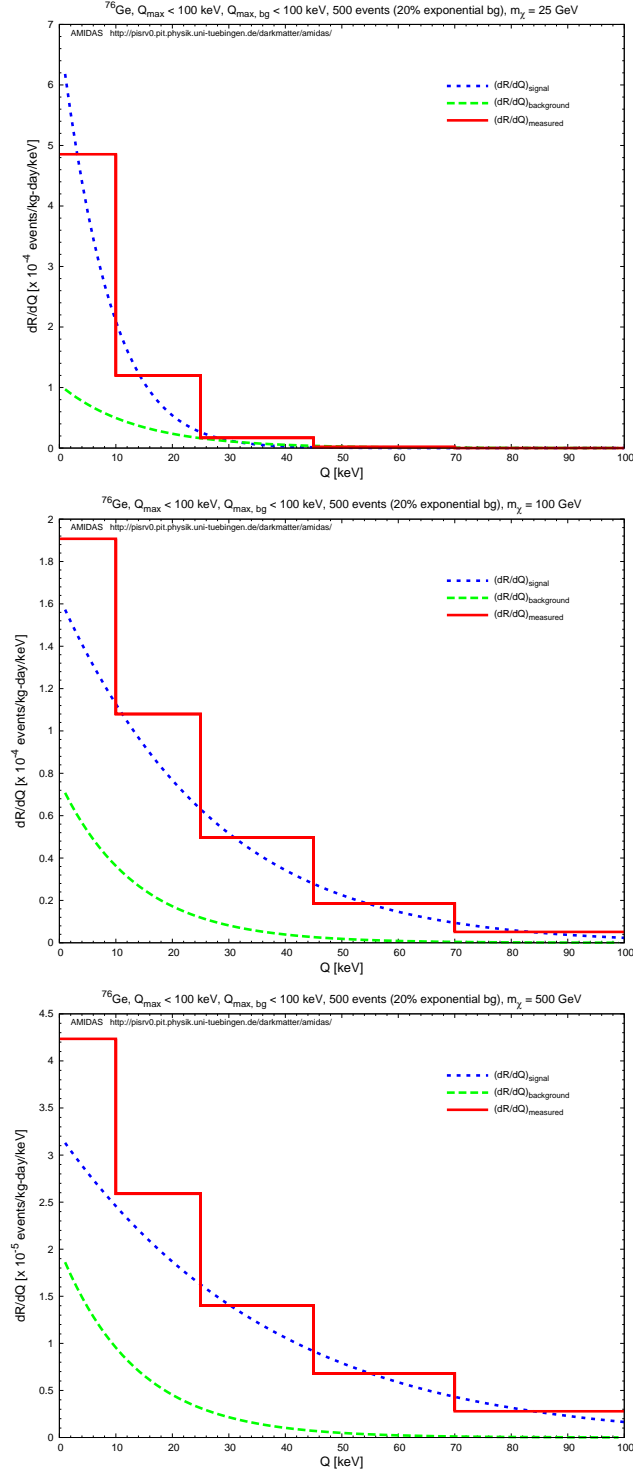
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Fig. 1. Measured energy spectra (solid red histograms) for a  $^{76}\text{Ge}$  target with three different WIMP masses: 25 (top), 100 (middle), and 500 (bottom) GeV. The dotted blue curves are the elastic WIMP-nucleus scattering spectra, whereas the dashed green curves are the exponential background spectra normalized to fit to the chosen background ratio, which has been set as 20% here (plots from Ref. 8).

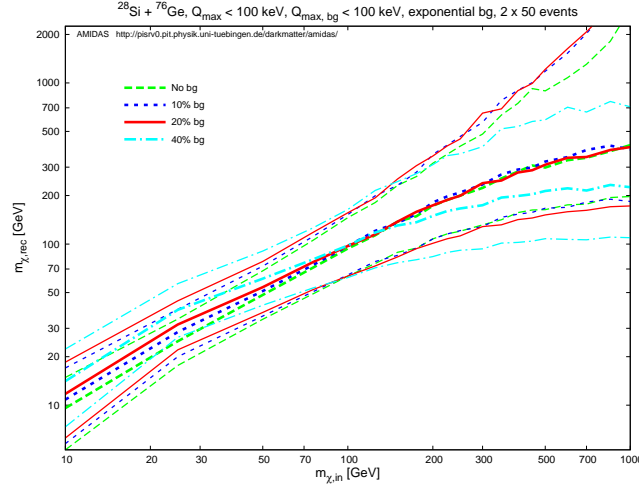


Fig. 2. The reconstructed WIMP masses as functions of the input WIMP mass.  $^{28}\text{Si}$  and  $^{76}\text{Ge}$  have been chosen as two target nuclei. The background ratios shown here are no background (dashed green), 10% (long-dotted blue), 20% (solid red), and 40% (dash-dotted cyan) background events in the analyzed data sets. Each experiment contains 50 total events on average. Other parameters are as in Figs. 1 (plot from Ref. 8).

background events as functions of the input WIMP mass. As in Refs. 2,  $^{28}\text{Si}$  and  $^{76}\text{Ge}$  have been chosen as two target nuclei. The background ratios shown here are no background (dashed green), 10% (long-dotted blue), 20% (solid red), and 40% (dash-dotted cyan) background events in the analyzed data sets.  $2 \times 5,000$  experiments with 50 total events on average in each experiment have been simulated.

It can be seen here clearly that, since for *light* WIMP masses ( $m_\chi \lesssim 100$  GeV), due to the relatively flatter background spectrum (compared to the scattering spectrum induced by WIMPs) or, in practice, some background sources in high energy ranges, the energy spectrum of all recorded events would mimic a scattering spectrum induced by WIMPs with a relatively *heavier* mass, the reconstructed WIMP masses as well as the statistical uncertainty intervals could be *overestimated*. In contrast, for *heavy* WIMP masses ( $m_\chi \gtrsim 100$  GeV), due to the relatively sharper background spectrum or e.g., some electronic noise, relatively more background events contribute to low energy ranges, the energy spectrum of all recorded events would thus mimic a scattering spectrum induced by WIMPs with a relatively *lighter* mass. Hence, the reconstructed WIMP masses as well as the statistical uncertainty intervals could be *underestimated*. Nevertheless, Fig. 2 shows that, with  $\sim 20\%$  residue background events in the analyzed data sets of  $\sim 50$  total events, the  $1\sigma$  statistical uncertainty band can cover the true WIMP mass pretty well; if WIMPs are light ( $m_\chi \lesssim 200$  GeV), the maximal acceptable fraction of residue background events could even be as large as  $\sim 40\%$ .

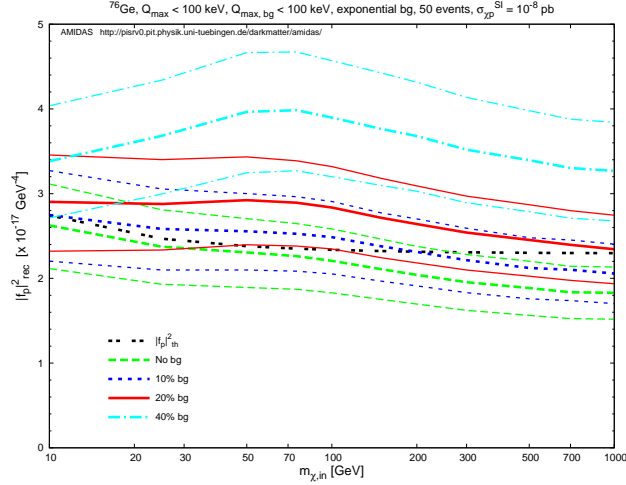
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Fig. 3. The reconstructed SI WIMP–nucleon coupling as functions of the input WIMP mass. The double-dotted black curve is the theoretical value of  $|f_p|^2$  corresponding to the fixed SI WIMP–nucleon cross section  $\sigma_{\chi p}^{\text{SI}} = 10^{-8}$  pb. The background ratios shown here are no background (dashed green), 10% (long-dotted blue), 20% (solid red), and 40% (dash-dotted cyan) background events in the analyzed data set. Each experiment contains 50 total events on average. Other parameters are as in Figs. 1 (plot from Ref. 9).

### 2.3. On estimating the SI WIMP–nucleon coupling

In this section I show the *median* values of the reconstructed SI WIMP–nucleon coupling with its  $1\sigma$  statistical uncertainty by means of the model-independent method introduced in Refs. 3 with mixed data sets. The SI WIMP–nucleon cross section for our simulations is set as  $10^{-8}$  pb, the standard value for the local WIMP density,  $\rho_0 = 0.3$  GeV/cm<sup>3</sup>, has been used for both the simulations and data analyses. As in Refs. 3, a <sup>76</sup>Ge nucleus has been chosen as our detector target for reconstructing  $|f_p|^2$ ; while a <sup>28</sup>Si target and a *second* <sup>76</sup>Ge target have been used for determining  $m_\chi$ . The background ratios shown here are no background (dashed green), 10% (long-dotted blue), 20% (solid red), and 40% (dash-dotted cyan) background events in the analyzed data set(s).  $(3 \times) 5,000$  experiments with 50 total events on average in each experiment have been simulated.

#### 2.3.1. With a precisely known WIMP mass

In Fig. 3 we first assume that the required WIMP mass for estimating  $|f_p|^2$  has been known precisely from other (e.g., collider) experiments with an overall uncertainty of 5% of the input (true) WIMP mass. It can be found in Fig. 3 that the *larger* the background ratio in the analyzed data set, the more strongly *overestimated* the reconstructed SI WIMP–nucleon coupling for *all* input WIMP masses. This can be understood as follows. For a given WIMP mass and a specified target nucleus, the SI WIMP–nucleus cross section is proportional to the total event number-to-exposure

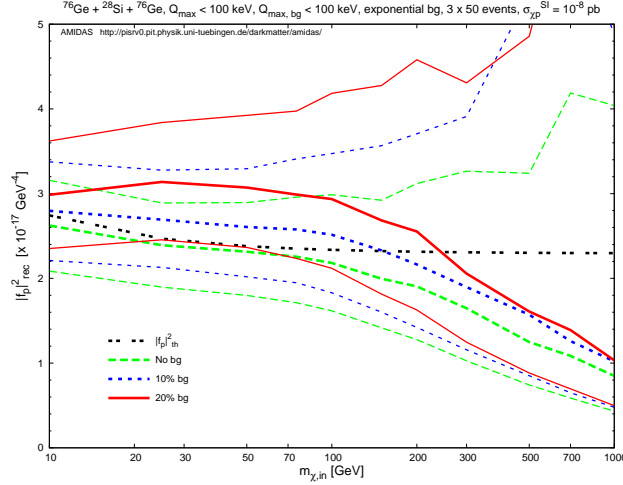


Fig. 4. As in Fig. 3, except that the WIMP masses have been reconstructed by means of the procedure introduced in Refs. 2 (plot from Ref. 9).

ratio. For a fixed number of total “observed” events, the *larger* the background ratio, or, equivalently, the *smaller* the number of real WIMP-induced events, the *smaller* the required exposure for accumulating the total observed events, and, therefore, the *larger* the estimated SI WIMP cross section/coupling. In other words, due to *extra unexpected* background events in our data set, one will use a *larger* number of total events to estimate the SI WIMP-nucleon coupling, and thus *overestimate* it.

Moreover, it can also be seen in Fig. 3 that, in contrast to the reconstructed WIMP mass shown in Fig. 2, where for an input WIMP mass of  $\sim 100$  GeV the effect of background events would be the smallest, the reconstructed SI WIMP-nucleon coupling would interestingly have the *largest deviation* for input WIMP masses between  $\sim 50$  GeV to 100 GeV, once the background ratio rises to  $\gtrsim 20\%$  (the dash-dotted cyan curves).

### 2.3.2. With a reconstructed WIMP mass

In Fig. 4 the required WIMP mass for estimating  $|f_p|^2$  has been reconstructed with *other* direct detection experiments. As shown in Fig. 2, due to the contribution from residue background events, if the input WIMP mass is *light/heavy*, the reconstructed mass would be over-/underestimated. Hence, for input masses  $\lesssim/\gtrsim 150$  GeV, the SI WIMP-nucleon coupling reconstructed by using three independent data sets would be *larger/smaller* than that reconstructed by using only one data set with extra information about the WIMP mass (cf. Fig. 3). In addition, the statistical uncertainty on the reconstructed SI WIMP coupling would also be (much) *larger*. However, Fig. 4 indicates that one could in principle estimate the SI WIMP-nucleon coupling with an uncertainty of a factor  $\lesssim 2$  by using three independent data sets with maximal 20% background events. For a WIMP mass of 100 GeV and a residue

background ratio of 20%, the deviation of the reconstructed SI WIMP coupling (with a reconstructed WIMP mass) would in principle be  $\sim +13\%$  with a statistical uncertainty of  $\sim {}^{+21\%}_{-14\%}$  ( $\sim -3.3\% {}^{+18\%}_{-13\%}$  for background-free data sets).

### 3. Summary

In this article we reexamine the data analysis methods introduced in Refs. 2, 3 for determining the mass of Dark Matter particle and its spin-independent coupling on nucleons from measured recoil energies of direct detection experiments directly, by taking into account small fractions of residue background events, which pass all discrimination criteria and then mix with other real WIMP-induced events in the analyzed data sets.

Our simulations show that, with a background ratio of  $\sim 10\% - 20\%$  in data sets of only  $\sim 50$  total events, while the  $1\sigma$  statistical uncertainty band of the reconstructed WIMP mass can cover the true value pretty well, especially for an input mass of  $\sim 100$  GeV, the reconstructed SI WIMP coupling on nucleons would be  $\sim 10\% - 15\%$  overestimated and the deviation would be the largest once the WIMP mass is between 50 and 100 GeV.

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